Acoustic Dopplergram for Intruder Defense

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Abstract - **In this paper, the concept of acoustic Dopplergram is introduced for active detection and tracking of an underwater vehicle from fixed platforms. Past experimental data collected at sea are used to illustrate the Dopplergram and determine the Doppler resolution as well as range resolution in target tracking. As an application, the Dopplergram will be used to detect a fast moving underwater intruder in a harbor environment for ship protection.**

I. INTRODUCTION

The challenge for an active system is the detection of a target echo amid the noise and/or the reverberation signals. In a noise limited situation, one needs a high source level, but in practice there is only so much power one can put out due to hardware and environmental (marine mammal) limitations. In a reverberation limited environment, increasing the source level does not necessarily help; the problem is the high probability of false alarms due to reverberations. In this paper, we introduce the concept of active detection for a fast moving (> 2 knots) object using the acoustic Dopplergram. In the Doppler space, the target echo is well separated from that of the noise or the reverberation; the later has a small (near zero) Doppler shift when ensonified from fixed sources and received on fixed hydrophones. The target Doppler as a function of time (the Dopplergram) can be used to uniquely track the target despite the low signal-to-noise (SNR) and signal-to-reverberation (SRR). The system can thus tolerate a higher noise and reverberation level than current systems based on energy detectors.

Current active systems adapt a "ping and listen" strategy, namely, the system sends out a short pulse signal and then listens; one looks for the target echo amid the reverberation returns. The expectation is that the target echo will stand above the noise and reverberation background, and can be detected/classified with some signal processing. The problem is that the reverberation return contains many signals which look like the target echo. While a target with a high target-strength can be easily detected by the echo SNR/SRR, a weak target with a low SNR/SRR is not easily recognized in the reverberation returns. The false alarm is a serious problem. The problem becomes worse when using a high-resolution sonar system. A narrower beam ensonifies a smaller area making the scattered-returns (from the bottom) look more like the echo from a target, thus resulting in a higher probability of false alarm.

The clutter problem is familiar in passive signal detection. High SNR narrowband signals can be easily detected in the frequency domain by the signal spectrum. The detection of low SNR signals becomes questionable as the signals at a level comparable to the noise level are difficult to detect using snapshots of the signal spectrum; they look like the noise. The detection of low level narrowband tonal signals (as well as wideband transient signals) can be significantly improved using the so call Lofargram (a gray scale plot of frequency spectrum with time) which has been widely used in the sonar world. The concept is based on the observation that noise spectral peaks are random in time while the signal spectral peaks are persistent over time. The signal is then detected by line-association (often referred to as eyeball integration) using the Lofargram. This concept for passive signal detection is carried forward to active signal detection in this paper. Following the Lofargram concept, we develop the Dopplergram which displays continuously the Doppler frequency shift as a function of time so that a weak echo-return from a target can be detected using eyeball integration. The Dopplergram will be used with the so called continuous broadband sonar where a broadband signal is continuously transmitted [1]. This mode of operation is called "transmit and listen". In this case, the target echo and reverberation are not apparently separated in time as in "ping and listen" and must be separated by other means [2]. We propose to separate the target and reverberation using Doppler frequency and for that purpose, the continuous sonar will transmit a signal from fixed directional sources and will receive the signal on fixed directional receivers. Assuming that reverberations originate predominantly from scattering off bottom-fixed objects and thus have near zero Doppler shifts, a fast approaching object (an underwater vehicle) can be detected based on the (non-zero) Doppler shift. A trace of the signals outside of the band centered at zero Doppler is a clear evidence of the presence of a fast moving object. The sidelobe level of the noise and reverberation in the Doppler domain is expected to be smaller than that in the beam domain.

II. CONTINUOUS SONAR

In the "transmit and listen" mode, the transmitter is on continuously. The continuous sonar is particularly interesting if it uses certain waveforms with high time-

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bandwidth product to provide a high processing gain. In active detection, to obtain a high range resolution, a wide band pulse is often used as it yields a high temporal resolution (proportional to the inverse of the bandwidth). The down side is that it has a poor frequency resolution (proportional to the inverse of the pulse duration). A pulsed CW (continuous wave) normally has a high frequency resolution, but poor temporal resolution. Both have a time bandwidth product, BT =1. A wide band dispersed waveform, such as linear frequency modulation (LFM) or pseudo-random binary phase-shift waveform based on m-sequence modulation (referred to as the m-sequence signal for short), can be constructed with BT > >1, providing both high temporal and frequency resolution. Of the two, the LFM has a poor Doppler resolution but the m-sequence signal has a good Doppler resolution. The other advantage of the m-sequence is that the signal is almost orthogonal to its cyclically shifted sequence, yielding a very low sidelobe level in its auto-correlation function. Hence, a waveform such as m-sequence or Gold sequence will be adapted for active systems employing the Dopplergram detection scheme.

A system concept for ship protection against a speedy underwater vehicle is depicted in Fig. 1 where a directional projector and directional receivers (e.g., two horizontal arrays) are deployed from the ship. The system is anticipated to possess: (1) a high probability of detection due to the 20-30 dB processing gain, (2) a low false alarm rate, due to the fact that no natural signal or noise can generate high Doppler shift, and (3) continuous tracking of the target in range and bearing, due to the high repetitive sounding of the continuous sonar.

The continuous sonar concept has likely been considered before, but it has not been successfully demonstrated or implemented in practice. A major problem is that the direct blast signal easily masks the echo return signal. In the “ping and listen” mode, the echo signal is separated in time from the direct blast signal. In the “transmit and listen mode” the direct blast signal is on continuously. Thus the key to the success of the continuous sonar is to minimize the direct blast signal so that the target echo is detectable. DeFerrari proposed to use the hyperspace coordinate zeroing method to remove the direct blast signal; simulation has show a > 60 dB rejection capability [2]. For practical consideration, we propose to use a directional source and receiver, each with 30 dB sidelobe suppression in the direction of the receiver/source. In addition, we will rely on the processing gain to detect the weak echo return. Below, we use the sonar equation to determine the source level and sidelobe rejection required for the continuous sonar:

$$SL + TL_0 + SLL_S + SLL_R < SL + 2x\ TL + TS + DI + PG > NL. \tag{1}$$

In Eq. (1), the first term is the level of the direct blast signal, where SL is the source level (of the main lobe directed toward the target), SLL_S represents the sidelobe level of the source in the direction of the receiver, SLL_R represents the sidelobe level of the receiver in the direction of the source, and TL_0 is the transmission loss from the source to the receiver. The second term in Eq. (2) is the signal level of the target echo; TL is the one-way transmission loss fro the source to the target, TS is the target strength, DI is the direction index of the receiver array and PG is the processing derived from temporal processing of the signal waveform. The last term denotes the NL in the direction of the target. Equation (1) says that the target echo must be larger than the direct blast signal leaked to the receiver and must be louder than the noise level.

We note that the left inequality is independent of the source level, SL. Assume a water depth of 30m. For a directional source ensonifying a target at a range of a few kilometers, it is reasonable to assume spherical spreading for the transmission loss up to 30 m and cylindrical spreading beyond 30m. For example, at a range of 3 km, TL = -50 dB and TL_0 = -26 dB. Assume the continuous sonar transmits repeated m-sequences, with a code length of 511, one expects a 27 dB processing gain; experimental measurements yield a 26 dB processing gain [3]. One then finds that the left inequality can be satisfied if the source and receiver has sidelobe rejection > 21 dB in the direction to each other. The right equality in Eq. (1) sets the minimum source level. Assume a noise level of 55 dB, one finds that the minimum source level is 127 dB, which can be easily accomplished.

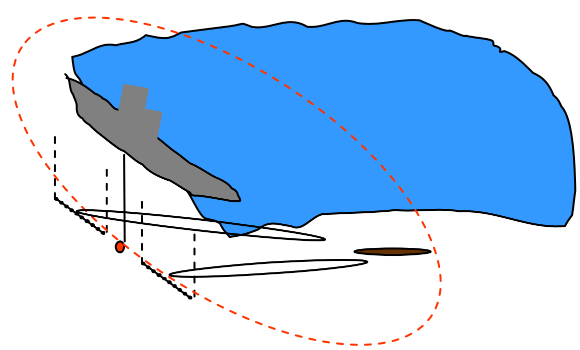

Fig. 1 The source-receiver configuration for a ship protection system

An experiment similar to that depicted in Fig. 1 is planned for the last quarter of 2007 to test the continuous sonar Dopplergram detection concept. The first objective is to determine whether the scattered return from a moving underwater object is detectable using continuous sonar, using directional transducers with 30 dB sidelobe rejection in the direction between the source and receiver.

III. ACOUSTIC DOPPLERGRAM

In this section, the acoustic Dopplergram concept is presented using previous data collected at sea to illustrate target detection and tracking. The signal is from an “echo repeater” towed by a ship. Normal echo repeater will trigger on an incoming pulse signal and then transmit the receiver signal after a certain delay. For a continuous incoming signal, the echo repeater will broadcast the continuous signal; the repeater part is redundant.

We illustrate the Dopplergram processing using data collected during the TREX (time reversal experiment) 2004 off the coast of New Jersey. The sound speed profile is near a constant except toward the surface and bottom. The water depth is 70m. See Ref. [3] for more details. The experiment was set up using a fixed receiver and a moving source (the echo repeater) towed by a ship. Figure 2a shows the towed track of the “echo repeater” relative to the receiver; the echo repeater projects continuous m-sequence signals. The m-sequence data has a carrier frequency of 17 kHz and a bandwidth of 4 kHz. The m-sequence length is 1023. Figure 2b shows the range to the receiver based on GPS (solid curve). The range is also estimated using the two way travel timed by the m-sequence signals (dashed curve). The data was transmitted as part of an underwater acoustic communication experiment. It is used to illustrate the Dopplergram concept. For detecting an underwater vehicle, one expects to use a much higher carrier frequency (e.g., 60 kHz) with a wider bandwidth.

The m-sequence data are processed using the transmitted m-sequence signal (the replica) as the matched filter. The replica m-sequence is time-dilated with different Doppler shift. Figure 3 shows the ambiguity function (the matched filter output) as a function of the delay time and Doppler shit for one m-sequence. It shows a high sensitivity to the Doppler shift. One finds a Doppler shift of ~16 Hz, with a Doppler resolution of 3-4 Hz at the 3 dB level. Having determined the Doppler shift, one obtains the matched filtered output as a function of geotime (transmitted time) as shown in Fig. 4, which can be converted into a geotime and delay time plot, displaying the channel impulse response as a function of time. The arrival time of the first (or dominant) path for each m-sequence is used to determine the travel time from the echo repeater to the receiver, which is then converted to range by multiplying it with the mean sound speed.

The impulse response in Figure 3 is converted into an auto-correlation function as a function of Doppler shift. While Figure 3 displays only a small range of Doppler shift, the processing is done for a Doppler shift covering -30 Hz to 30 Hz. The auto-correlation function for the continuous m-sequences is plotted as a function of Doppler shift and geotime as shown in Fig. 5. This is the Dopplergram. It shows that a Doppler shift changing with time as the range changes between the echo repeater and the receiver. The echo return from a fixed object has a zero Doppler shift as shown in the middle of Fig. 6. The continuous tracking of the target in the Doppler space is a clear indication of a moving target.

IV. SUMMARY

Dopplergram is illustrated in this paper which can be used to detect a moving underwater vehicle from a fixed source and receiver. Sonar analysis is given for a continuous active sonar system projecting signals with a large time-bandwidth product. The advantage is a low source level due the processing gain derived from time compressing of the signal waveform. It provides a continuous estimation of the target range and also bearing, when equipped with a horizontal array or directional receivers. The target can be detected by a continuous trace in the Dopplergram, when the target is moving. The measured Doppler resolution of 3-4 Hz or 0.7 knots indicates that a target with a speed of >= 2 knots can be detected with high assurance. As noise and reverberation from fixed objects have little components in non-zero Doppler domain, the detection is less limited by neither the noise level nor the reverberation level compared with the energy detectors. In other word, the false alarm probability is lower in the Doppler domain than in the energy domain. The potential advantage will be evaluated in future experiments.

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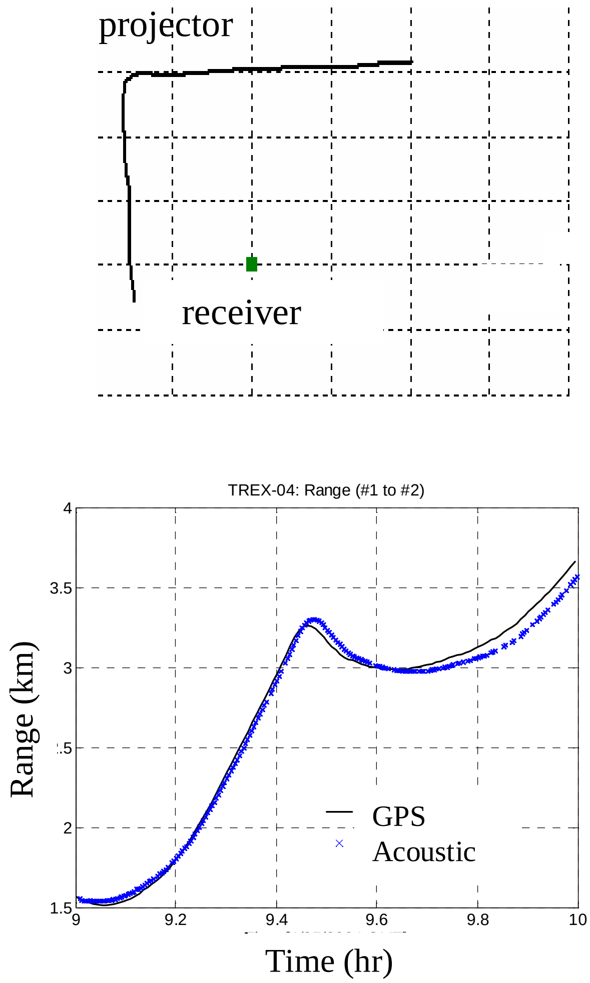

Fig. 2 (a) Track of the echo-repeater projector relative to the fixed receiver (top figure). (b) Bottom figure shows the range between projector and receiver determined from the GPS locations (solid line) and from the m-sequence signals (dashed line).

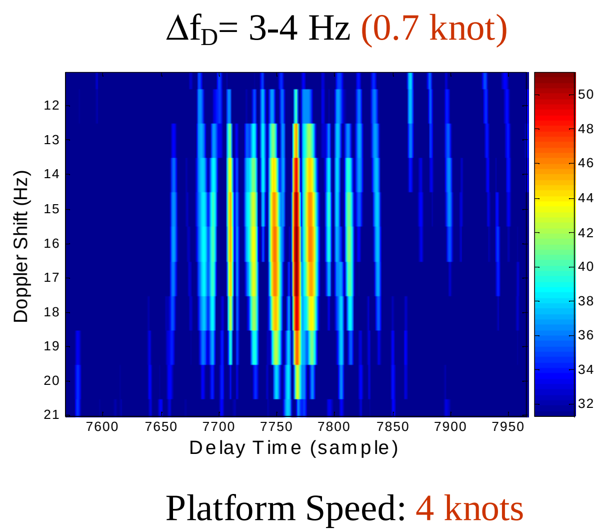

Fig. 3 Wide-band ambiguity surface as a function of the Doppler frequency and delay time.

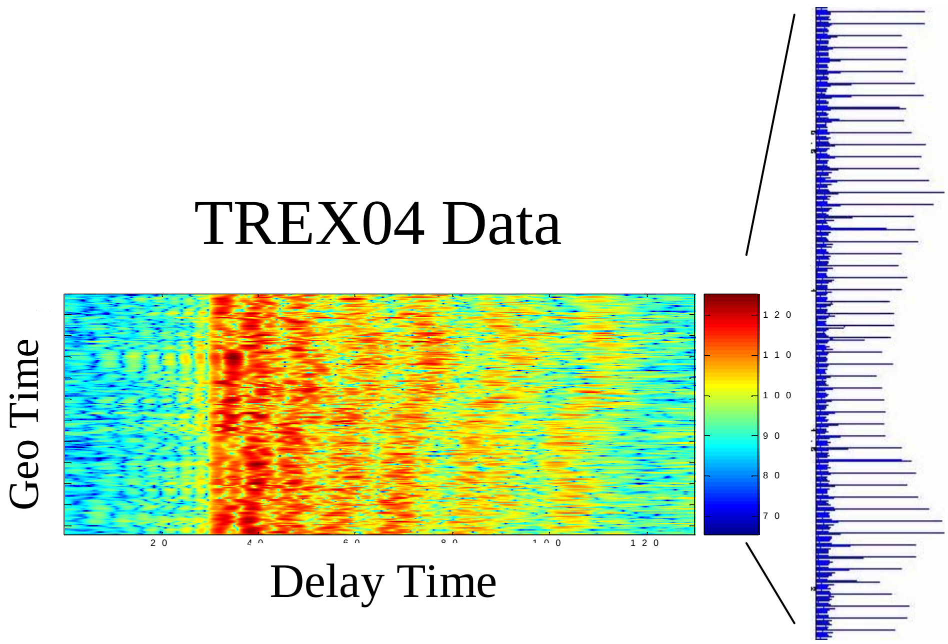

Fig. 4 Matched filter output time series (right figure). Individual impulse responses are plotted consecutively as a function of geotime and delay time (color figure).

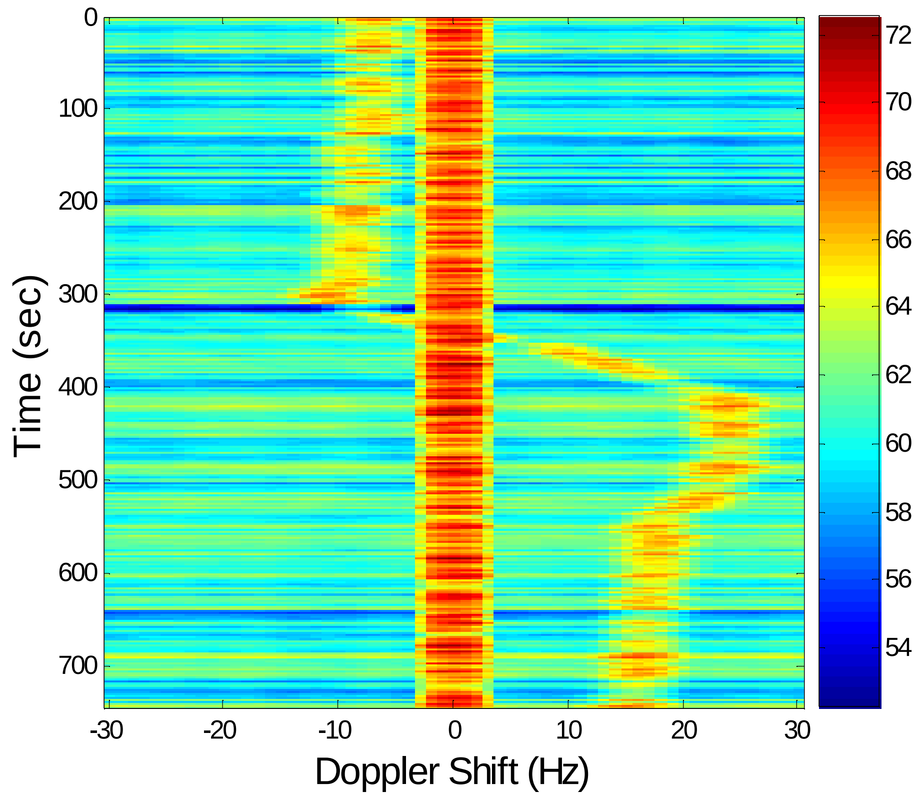

Fig. 5 Spectral gram as a function of Doppler frequency and geotime.